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SENERAL AMERICAN TRANSPORTATION CORPORATION

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NATURAL VENTILATION TEST OF AN ABOVEGROUND FALLOUT SHELTER IN CHICAGO, ILLINOIS

bу

R. H. Henninger C. A. Madson

GARD Report 1268-81

August 1966

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Prepared for Office of Civil Defense Department of the Army, OSA under Work Unit 1214A

SRI Subcontract No. B-64220(4949A-16)-US

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R. H. Henninger C. A. Madson

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Reviewed by:

G. Engholm

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Group Leader Environmental Research 1,000ml

Approved by:

General Manager

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This interim report describes environmental tests performed in a specific shelter. The discussion of the results is preliminary and should not be used as the basis for general conclusions. A subsequent final report will include a comparative evaluation of data from subsequent tests having a variety of configurations and locations.

FOREWORD

The natural ventilation tests reported herein were conducted by General American Research Division of General American Transportation Corporation,
Niles, Illinois, during the period of 12 July to 28 July 1965, under Stanford
Research Institute (SRI) Contract No. B-64220(4949A-16)-US. Mr. C. A. Grubb
of SRI monitored this Civil Defense project. The major objectives of this
shelter ventilation test program are: "(a) to evaluate parameters that determine
the resultant shelter environment, (b) to develop a rationale for estimating
minimum shelter equipment requirements, and (c) to obtain and correlate
experimental data in support of current or modified computational methods or for
direct use as empirical information". These tests were confined exclusively
to the evaluation of natural ventilation effects.

The authors wish to acknowledge the assistance provided by Mr. Walter Sterling, Housing Administrator and Mr. James Merutka, Superintendent of Fire Prevention and Safety for the University of Illinois, Medical Center Campus and also Mr. Philip Voegtle, Superintendent of Fire Prevention and Safety for the University of Illinois, Chicago Circle Campus. Through their efforts we were able to obtain the test site on the University's Medical Center Campus.

ABSTRACT

A 12-day natural ventilation test was conducted in a 275-occupant above-ground corridor-type shelter using wind forces only to supply ventilation air. This test is one in a series run to develop procedures to predict natural ventilation rates in aboveground shelters. An overall window ventilation efficiency (effectiveness factor) of 0.15 was determined experimentally with windows open on two walls. This effectiveness factor is independent of wind direction.

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Based upon the experimentally determined effectiveness factor and a total openable window area of 119 square feet, the shelter will be adequately ventulated by natural ventilation 98.2 per cent of the days during the year. That is, in the Chicago area, the effective temperature of this shelter when occupied by 275 people at 10 square feet per person will not exceed 83°F for more than seven days during an average year.

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SECTION 1

INTRODUCTION

Ventilation tests of an aboveground corridor-type fallout shelter located in Chicago, Illinois, were performed during the month of July 1966 to determine air temperatures, humidities, and ventilation rates obtained using natural ventilation through existing windows and corridors. Shelter occupancy was simulated by the use of electromechanical devices (Simocs) which duplicate the sensible and latent metabolic output of shelter occupants.

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Throughtout all tests, hourly data were recorded on wind speed and direction, ambient and shelter temperatures and humidities, and psychrometric conditions. The window ventilation efficiency was then determined.

SECTION 2

DESCRIPTION OF TEST SITE

The shelter tested was a portion of the fifth floor of the Student Residence Hall located in Chicago at the corner of Polk and Wolcott Streets on the Medical Center Campus of the University of Illinois (see Fig. 1). The test area consisted of the north and south wings of a T-shaped corridor and included 21 single and double bedrooms with individual closet space (see Figs. 2 and 3). A temporary plastic and plywood partition separated the test area from the rest of the fifth floor.

2.1 Occupancy Level

The total useable floor area of the north and south wings is 5200 square feet; however, only the corridor (800 feet square) and approximately half of each dormitory room (the half away from the windows) provides a protection factor of 40 or more (see Section 2.4) and therefore was considered to be occupied by shelterees during the test. Hence, the maximum occupied floor area was approximately 2750 square feet. At an occupancy loading of 10 square feet per person, the maximum number of occupants is 275.

2.2 Ventilation Openings

The only ventilation openings present in the shelter are 41 identical 50 inch by 39 inch double-hung windows (wooden sash type). Each of the 20 double bedrooms has two windows (see Fig. 4) while the single bedroom has only one window. Twenty-four windows are located in the east wall and 17 in the west wall of the shelter. Throughout the test, the upper sash of each window was closed. The bottom sash has a total openable area of 5.8 square feet.

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Figure 1 EXTERIOR VIEW OF STUDENT RESIDENCE HALL, CHICAGO, ILLINOIS

Figure 2 SHELLTER FLOOR PLAN AND INSTRUMENTATION

GRAPHIC PCALE DEST



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Figure 3 TYPICAL DORMITORY ROOM



Figure 4 TYPICAL SHELTER WINDOWS

Although stairwells are present at both ends of the corridor, they could not be used as ventilation openings since the other floors in the building were occupied by students during the entire test.

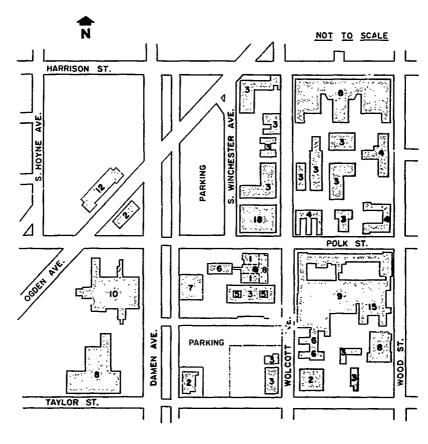
2.3 Shelter Surroundings

Fig. 5 shows the locations and heights of buildings surrounding the shelter. An eighteen-story building (see Fig. 6a) lies directly opposite the shelter and approximately 110 feet away on the north side of Polk Street.

Another large building, nine stories high, is located directly east of the shelter 190 feet away (see Fig. 6b). The nearest large buildings or obstructions south of the shelter are at least a clock away (see Figs. 6c and 6d). West of the shelter is the east wing of the Student Residence Hall which divides the west wall of the shelter (see Fig. 7) and a six-story dormitory which lies 160 feet from the west wall of the shelter. All other structures within half a block of the shelter are of height and location such that they would have little effect on the wind conditions at the shelter windows.

2.4 Radiation Protection

An analysis of the she ter's radiation protection factor was made by Mr. W. B. Cobb, Registered ALLOLT Shelter Analyst (see Appendix A). Half of each dormitory room (the half away from the window) has a protection factor of 42 and therefore qualifies as shelter space. The corridor, providing better protection, has a protection factor of 110. This made 2750 square feet of floor area available for occupancy.



LEGEND

- * WINDSCOPE AND WIND SPEED TRANSMITTER LOCATION ON ROOF
- SHELTER TEST SITE

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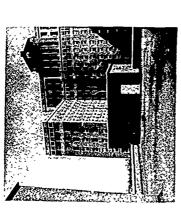
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SURROUNDING BUILDINGS - Number Indicates Height in Stories

Figure 5 PLOT OF BUILDINGS SURROUNDING SHELTER







(b) East View



VIEW FROM ROOF OF STUDENT RESIDENCE HALL



Southeast View (၁



(d) Southwest View

Figure 6

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Figure 7 EXTERIOR VIEW OF NORTHWEST CORNER OF STUDENT RESIDENCE HALL

SECTION 3

INSTRUMENTATION

3.1 Temperature Measurement

Shelter and ambient dry-bulb and wet-bulb temperatures were measured with nine aspirating psychrometers (Sargent Model S-42610), five of which were equipped with resistance type thermometers (Minco #1119) and the remaining four equipped with mercury-bulb glass thermometers. Three of each type were located within the shelter four feet above the floor (see Fig. 8), and the remaining three psychrometers were positioned outside windows of rooms 504 and 510 to measure ambient weather conditions (see Fig. 2). All resistance bulb readings were recorded continuously on a Honeywell strip-chart multi-point recorder.

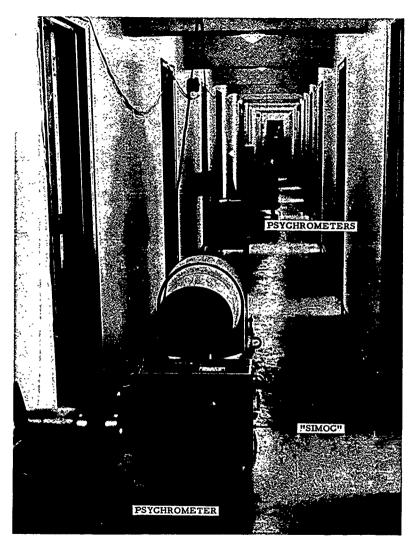
3.2 Shelter Energy and Moisture Inputs

Aggregate Simocs* (Ref. 1) were used to simulate the sensible and latent metabolic output of shelter occupants. Four Simocs were located along the corridor (Figs. 2 and 9) and adjusted to simulate uniform shelter loading of either 100 occupants or 185[†] occupants.

The total occupant energy input to the shelter was measured each hour with a kilowatt-hour meter (Sangamo Model #P3ODS, Class 200). This power input was adjusted, as required by line voltage variation, to maintain 400 Btu per occupant-hour.

^{*}Simulated Occupants

⁺Maximum number of occupants that could be simulated due to limited electrical power.



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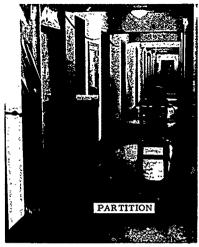
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Figure 8 INTERIOR VIEW OF SHELTER CORRIDOR LOOKING FROM SOUTH TO NORTH



Looking South Prom Center of Corridor



Looking North From Center of Corridor

Figure 9 OTHER INTERIOR VIEWS OF SHELTER CORRIDOR

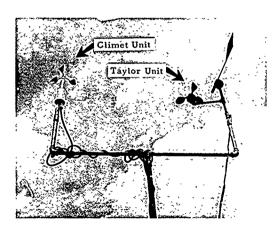


Figure 10 WIND INSTRUMENTS

During the entire test the shelter lighting and instrumentation loads were constant at 4780 Btu per hour.

The rate at which water (latent energy input) was discharged by the Simocs was measured hourly on a balance-beam platform scale. This rate was compared to the computed rate for 100 or 185 occupants, and the Simocs were adjusted as necessary to maintain the desired rate.

3.3 Wind Speed and Direction

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Wind instruments (see Fig. 10) were placed on the penthouse roof which is about 95 feet above ground level. The instrument stand extended another 20 feet into the air which enabled readings of wind speed and direction to be measured at an elevation of 115 feet above ground level.

A Taylor Windscope (Model 3105) and a Climet Wind Speed Transmitter (Model Oll-1) were placed atop the instrument stand. The Taylor Windscope gives instantaneous readings of wind speed and direction on a meter. The Climet Wind Speed Transmitter records an integrated time average wind speed on a digital counter.

SECTION 4

PROCEDURES

The eight tests that were conducted evaluated the effects of natural ventilation. These tests are summarized in Table 1.

4.1 Data Recording

The shelter and ambient air dry-bulb and wet-bulb temperatures and water input to the Simocs were logged hourly. The total Simoc power was also recorded each hour from the kilowatt meter. Every hour the average wind speed and direction were recorded during a one minute observation; in addition, an hourly integrated value of the wind speed was recorded with the Climet Wind Speed Transmitter.

From the U.S. Weather Bureau at Midway Airport, 7.6 miles southwest of the shelter, hourly conditions of the wind speed and direction were obtained and compared to the observations at the shelter site.

Psychrometric air properties were determined from the shelter average dry and wet-bulb temperatures using the ASHRAE Psychrometric Chart No. 1 (Ref. 2). Effective temperatures and humidity ratios were determined from tables developed by GARD (see Appendix B).

4.2 Determination of Ventilation Rate

The natural ventilation rate was calculated by the steady-state tracer gas technique using water vapor as the tracer gas (Ref. 3). The increase in shelter humidity ratio over ambient humidity ratio is related to the average

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				:			open 21, 5 inches open 21, 5 inches			open 21, 5 inches, 5 inches, and & 528) open 21, 5 inc	k 535) open 21, 5 inch- open 21, 5 inches, and , 524, 527, & 529) open 21, 5 inches	One window in each of twenty-one rooms open 21, 5 inches			
D				ENINGS **			531 4 532)			531 & 534) 6) open 21. .521, 524,	531, 533, 4 515 4, 517) 520, 522,	-one room			
				Ventilation openings **	pen 3 inchei	All 41 windows open 6 inches	4 windows on NW wall (rms. 531 & 532) open 21, 5 inches 4 windows on SE wall (rms. 519 & 520) open 21, 5 inches	All 41 windows open 3 inches	All 41 windows open 6 inches	2 windows on NW wall (rms, 531 & 534) open 21, 5 inches, I window on SW wall (rm, 516) open 21, 5 inches, and 3 windows on East wall (rms, 521, 524, & 528) open 21, 5 inches	3 windows on NW wall (rms, 531, 533, & 535) open 21.5 inches, 2 windows on SW wall (rms, 515 & 517) open 21.5 inches, and 5 windows on East wall (rms, 520, 522, 524, 527, & 529) open 21.5 inches	h of twenty			
Cia				VENTIL	All 41 windows open 3 inches							ndow in eac			
1. 2.		rol .										One wit			
	н	Summary of Shelter Tests	ter Tests	ter Tests		"OCCUPIED" SHELTER AREA	Corridor	=	=	Corridor and approximately half the area of each room		ŧ	:	:	
Ñ	Table 1	of Shel			o	٥			•		<u> </u>				
		mary c		NUMBER OF OCCUPANTS	100	100	100	185	185	185	185	185			
3				TEST DURATION (HOURS)	48	24	80	\$0	48	48	21	16	which		
SE SE				ATE(S)	2 to 7/14	4 to 7/15	7 to 7/19	12/L ot 6	1 to 7/23	5 to 7/27	זנוו	7 to 7/28	Dimension given is the height to which bottom sash is raised above sill the bottom sash is raised above sill bottom.		
8			-	ů G	7/1:	1/1	7/1	1/1	7/2	1/2:	_	1/2	given is h is rais		
25.55 25.55				LOGSHEET NUMBER (S)	1,2	3	4,5,6	6,7,8	9,10	11, 12	13	14	• Dimension bottom sale		
8				ST 4BER 1	_	2	3	•	٠,	٠	2		•		
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shelter ventilation rate in accordance with the following equation:

$$Q = \frac{(v_o)(M_w)}{60(W_s - W_o)}$$
 (1)

where:

Q = ventilation rate, cfm

 $v_{o} = \text{specific volume of ambient air, } ft^{3}/\text{lb d.a.}$

 $M_w = \text{mass of water vapor supplied to shelter by Simocs, } 1b_w/hr$

 $W_{c} = \text{humidity ratio of shelter air, } lb_{w}/lb d.a.$

 W_{0} = humidity ratio of ambient air, lb_{W}/lb d.a.

Equation 1 assumes:

- 1. construction materials impervious to water vapor,
- 2. no water vapor diffusion through open windows,
- no moisture storage or release from the volume of the shelter air, and
- 4. no condensation of liquid water within the shelter.

The error introduced by the first and second assumptions is small when using the steady-state technique. The third assumption could introduce a considerable error when considered on an hourly basis; however, over a period of several hours or more, this error becomes insignificant. The fourth assumption was valid for the entire testing period.

SECTION 5

TEST RESULTS AND DISCUSSION

Natural ventilation moves air through buildings without the help of mechanical equipment. The forces of wind pressure and density (thermal) differences provide the necessary motive forces to move air through ventilation openings and into and through buildings.

Thermal forces are produced when sensible heat and water vapor are added to a volume of air causing it to become less dense, rise and displace denser air. In tall buildings where stairwells, elevator shafts and other ventilation openings provide paths for vertical movement of air, ventilation rates due to thermal forces can be significant. In this test, however, all stairwells and elevator shafts were closed to prevent any air movement due to thermal forces (see Section 2.2).

Since thermally motivated forces were excluded during the testing period, it was expected that the air forced through the shelter was due to wind effects alone. The quantity of air forced through a window or ventilation opening may be predicted by the equation (Ref. 4):

$$Q_{w} = EAV$$
 (2)

where:

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Q = air flow, cubic feet per minute

A = free area of inlets or outlets (assumed equal), square feet

V = wind velocity, feet per minute

E = effectiveness of openings (suggested values range from 0.25 to 0.60 depending upon the direction of the wind on the shelter) Corrections are presented in the ASHRAE Guide and Data Book for the effect of unequal inlet and outlet areas. This correction (F), expressed as a multiplier of (EAV) and which is always ≥ 1.0 , represents the increase in air flow above that which results for equal inlet and outlet areas (F = 1.0).

The prime objective of the data analysis is to establish a window effectiveness factor (E) for a corridor-type shelter. At first glance it might appear
that E is a function of only the angle at which the air approaches the opening,
and for the most part this is true; however, other influences such as the type
of ventilation opening, the internal configuration of the shelter, the exterior
shelter surroundings and the density of occupancy loading can all have an
effect on the value of E. To separate these effects is a complex task.

To empirically determine the opening effectiveness, E in equation 2, the data was grouped according to wind direction. These data groupings were then plotted as ventilation rate per square foot of window area versus wind velocity. With the inclusion of appropriate constants, the slope of the least-squares curve fit to the data then represents the window effectiveness factor E.

5.1 Directionally Dependent E-Factor

Previous investigations (Refs. 5 to 8) have indicated that the window effectiveness factor is a function of the angle at which air approaches a ventilation opening. To further evaluate this effect the data was grouped into 16 wind direction intervals. These intervals included the 45° over-

lapping wind sectors of

NNW-N-NNE NNE-NE-ENE ENE-E-ESE ESE-SE-SSE SSE-S-SSW SSW-SW-WSW WSW-W-WNW WNW-NW-NNW

and the 90° overlapping wind sectors of

NW-N-NE N-NE-E NE-E-SE E-SE-S SE-S-SW S-SW-W SW-W-NW W-NW-N

The data points included in each of these sixteen wind direction intervals were then fit with a linear least squares curve (linear because equation 2 indicates that Q should be a linear function of V). Figs. 11 to 18 depict the least squares curve fit for the 90° sectors and present the effectiveness factor which was determined by the slope of the curve.

Table 2 summarizes numerically the results for the sixteen intervals for an assumed equal inlet-outlet window pattern (F = 1.0) and for various limits of experimental error as determined in Section 5.4. As the value of $\left[W_S-W_O\right]$ is decreased, the maximum possible experimental error increases. Hence, the results listed in Table 2 for $\left[W_S-W_O\right] \ge 0.00200$ have the least possible experimental error.

Based upon the data collected during the limited testing period, it appears that the 90° wind sector results give a truer indication of the E-factor than the results for the 45° wind sectors. This conclusion is based upon two observations: first, the range of E for the 90° sectors is in closer agreement with the physical conditions which actually surround the shelter and second, too few data points are available for certain sectors of the 45°

analysis to put much faith in their results. Subsequent analysis is therefore based upon the values of E obtained with the 90° wind sector analysis for $\left[W_S-W_O\right] \geq 0.00200$.

Table 3 summarizes the same data groupings as were used in Table 2, using, however, the actual inlit-outlet window pattern which existed during the test as determined by hourly observations. Comparison of the two tables show that the experimental values of E remain almost the same for the results with $\begin{bmatrix} w_s - w_o \end{bmatrix} \geq 0.00200.$ This indicates that the open window area was split evenly between inlets and outlets during most of the testing period.

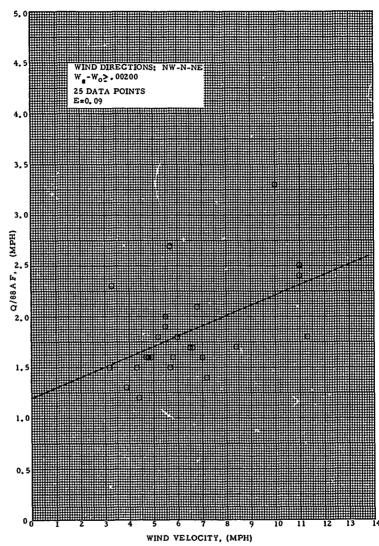
5.2 Overall E-Factor

During any designated time period (whether it be for a day, week, month or year), the wind direction does not remain constant, therefore, the calculation of average ventilation rates based upon the directional E-factors would have little value. An overall or average E which is independent of wind direction would have more applicability.

An overall E-factor of 0.15 was calculated for this shelter with a least squares analysis similar to that discussed previously. The overall E was determined by a least squares fit of all data points from all wind directions with a value of $\begin{bmatrix} W_S - W_O \end{bmatrix} \ge 0.00200$ (see Fig. 19).

5.3 Comparison of Local and Weather Bureau Data

Local wind speed and direction data were obtained from the U.S. Weather Bureau located at Midway Airport which is 7.6 miles southwest of the shelter. In addition, observations of wind speed and direction were made at the shelter



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Figure 11 CORRELATION OF DATA FOR NW-N-NE WIND SECTOR

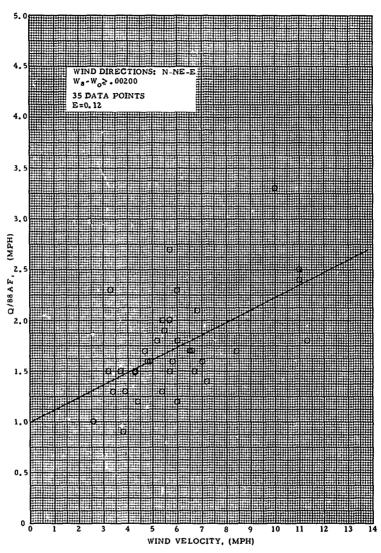
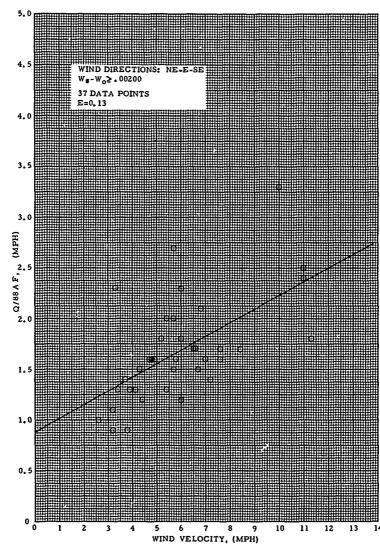


Figure 12 CORRELATION OF DATA FOR N-NE-D WIND SECTOR



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Figure 13 CORRELATION OF DATA FOR NE-E-SE WIND SECTOR

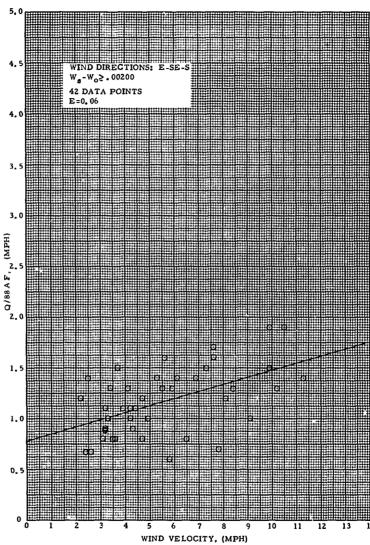
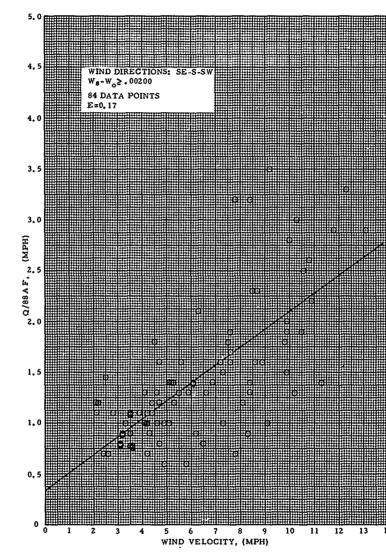


Figure 14 CORRELATION OF DATA FOR E-SE-S WIND SECTOR



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Figure 15 CORRELATION OF DATA FOR SE-E-SW WIND SECTOR

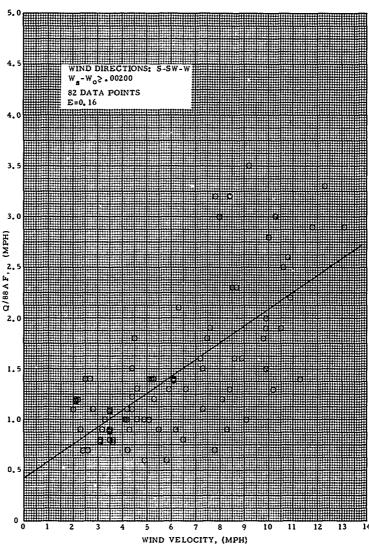
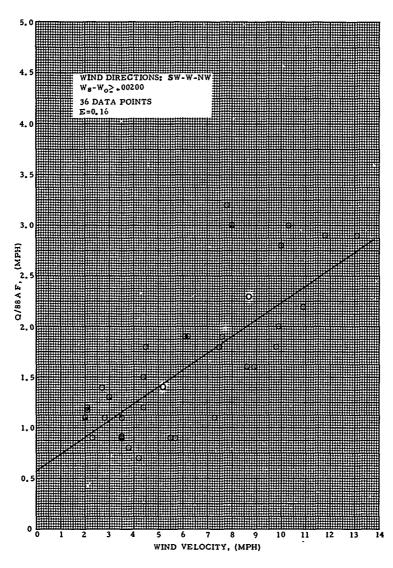


Figure 16 CORRELATION OF DATA FOR S-SW-W WIND SECTOR



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Figure 17 CORRELATION OF DATA FOR SW-W-NW WIND SECTOR

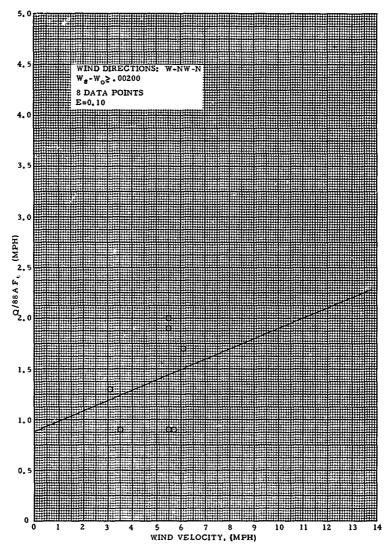
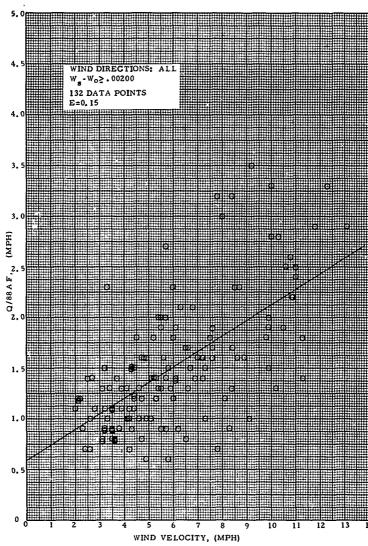


Figure 18 CORRELATION OF DATA FOR W-NW-N WIND SECTOR



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Figure 19 CORRELATION OF DATA FOR ALL WIND SECTORS

Table 2 DIRECTION DEPENDENCE OF E-FACTOR (for F = 1.0)

		Humidit	y Difference - 1b / 1b	d.a. [Ws-Wo]
Wind Directions ALL		≥ .00200	≥ .00150	> .00100 ·
		0.15 (132)	0.15 (164)	0.24 (225)
NNW-N-NNE NNE-NE-ENE ENE-E-ESE ESE-SE-SSE SSE-S-SSW SSW-SW-WSW	Wind Sectors	0.21 (4) 0.12 (32) 0.19 (12) 0.13 (11) 0.16 (55) 0.20 (50)	0.24 (6) 0.17 (49) 0.32 (17) 0.15 (12) 0.15 (59) 0.21 (55)	0.33 (17) 0.22 (73) 0.49 (23) 0.15 (12) 0.16 (66) 0.21 (69)
wsw-w-wnw wnw-wn-wnw	<u>,</u> 54	0.12 (11) 0.10 (4	0.12 (15) -0.03 ⁻ (7)	0.15 (24) 0.13 (15)
NW-N-NE N-NE-E NE-E-SE E-SE-S SE-S-SW S-SW-W SW-W-NW	90° Wind Sectors	0.09 (25) 0.12 (35) 0.13 (37) 0.06 (42) 0.17 (84) 0.16 (82) 0.16 (36) 0.10 (8)	0.15 (41) 0.18 (54) 0.18 (55) 0.07 (46) 0.18 (91) 0.17 (91) 0.17 (44) 0.16 (14)	0.21 (73) 0.27 (89) 0.25 (79) 0.20 (53) 0.18 (105) 0.17 (109) 0.16 (63) 0.27 (30)

NOTES: Number of hourly data points for each correlation are given in parenthesis.

Results are for all tests, day and night hours, and for all wind velocities.

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Wind		Humidity Difference - lb _w /lb _{d.a.} (W _s -W _o)									
Directions		≥ .00200	≥ .00100								
ALL		0.15 (132)	0.21 (164)	0.26 (225)							
NNW-N-NNE		0.18 (4)	0.34 (6)	0.40 (17)							
nne-ne-ene	rs Si	0.11 (32)	0.29 (49)	0.26 (73)							
ENE-E-ESE	Sectors	0.23 (12)	0.44 (17)	0.60 (23)							
ESE-SE-SSE		0.09 (11)	0.11 (12)	0.11 (12)							
SSE-S-SSW	Wind	0.18 (55)	0.17 (59)	0.18 (66)							
SSW-SW-WSW		0.25 (50)	0.26 (55)	0.25 (69)							
wsw-w-wnw	145°	0.12 (11)	0.12 (15)	0.19 (24)							
WMN-WW-NWW		-0.07 (4)	-0.13 (7)	0.13 (15)							
NW-N-NE		0.09 (25)	0.25 (41)	0.24 (73)							
n-ne-e		0.12 (35)	0.30 (54)	0.33 (89)							
ne-e-se	Sectors	0.11 (37)	0.29 (55)	0.31 (79)							
E-SE-S	ect	-0.01 (42)	0.00 (46)	0.16 (53)							
SE-S-SW		0.17 (84)	0.17 (91)	0.18 (105)							
S-SW-W	Wind	0.16 (82)	0.17 (91)	0.17 (109)							
SW-W-NNW	90°	0.15 (36)	0.16 (44)	0.16 (63)							
W-NW-N	5	0.11 (8)	0.16 (14)	0.28 (30)							

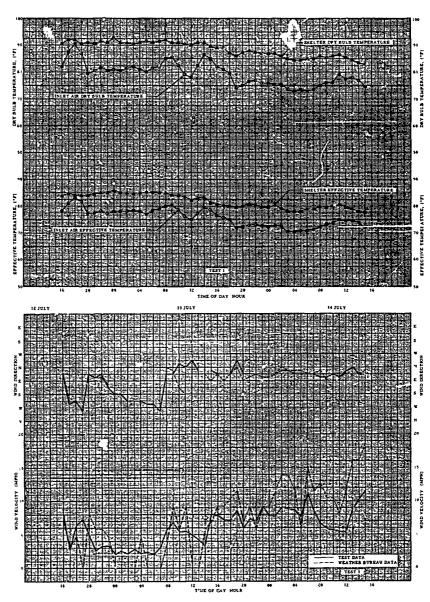
NOTES: Number of hourly data points for each correlation are given in parenthesis.

Results are for all tests, day and night hours, and for all wind velocities.

and compared to the Weather Bureau observations. The temperature and wind conditions, which existed during the testing period are presented in Figs. 20 to 26.

Good correlation between Weather Bureau and shelter observed wind direction were obtained even when the local wind <u>direction</u> was such that the shelter was shielded by adjacent buildings. Wind <u>speed</u> observations compared favorably except when the wind was out of the north or northeast where the shelter was shielded. For these directions, the Weather Bureau readings were approximately 5 mph greater than those observed at the shelter.

During the twelve day testing period, the average wind speed recorded at the shelter was 7.4 mph; the average wind speed as recorded at the Weather Bureau for the same period was 9.7 mph. The difference in agreement is probably due to the shielding effects which existed during certain wind periods and also due to the manner in which the two readings were recorded. The Weather Bureau's determination is an instantaneous reading taken once every hour on the hour for a one minute interval. The shelter observation is an interval or average determination which was recorded over the entire hour by the Wind Speed Transmitter. The shelter observation would give a truer indication of the average wind speed. Difference in readings may also be due to the Weather Bureau observations being made at a point 20 feet above-grade while the shelter observations were made 95 feet above-grade.



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Figure 20 TEST 1 TEMPERATURES AND WIND CONDITIONS
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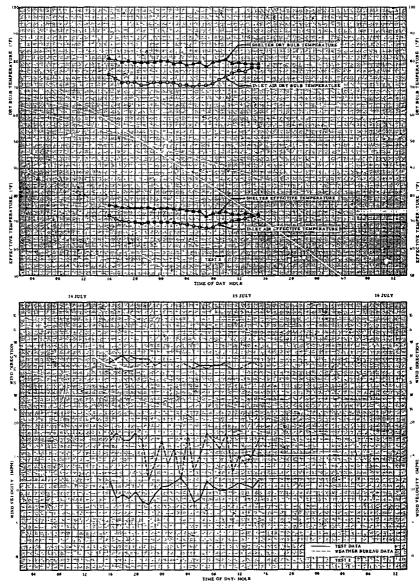
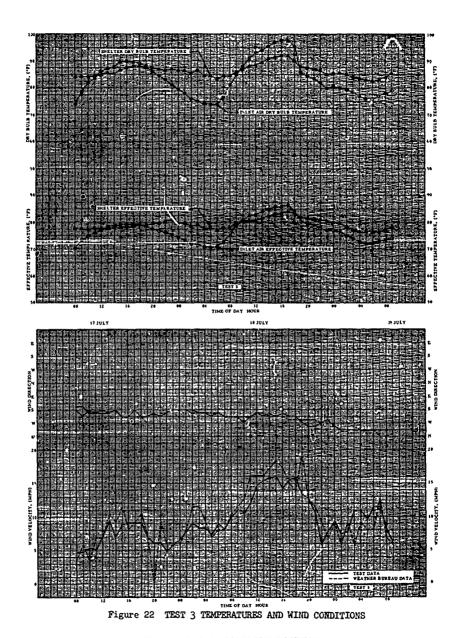


Figure 21 TEST 2 TEMPERATURES AND WIND CONDITIONS

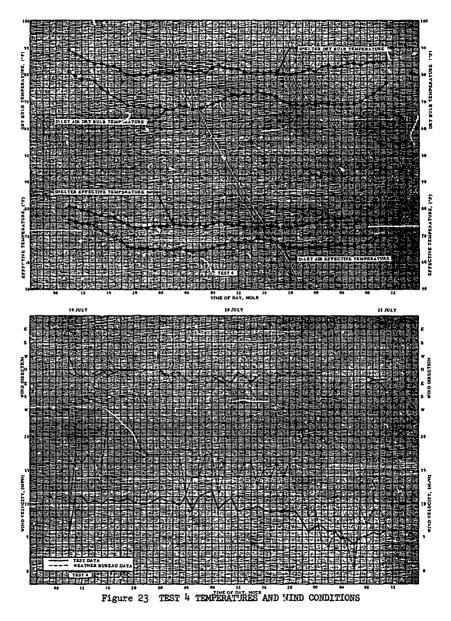


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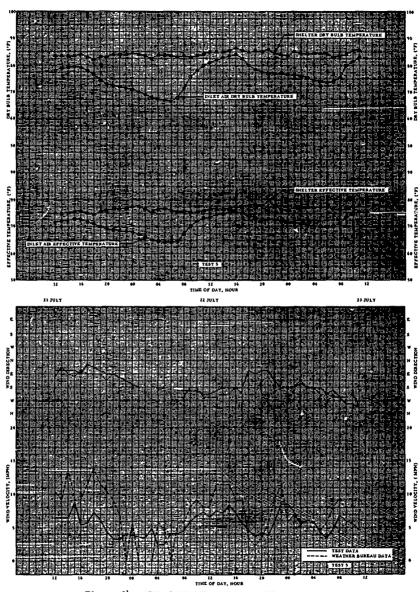
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Figure 24 TEST 5 TEMPERATURES AND WIND CONDITIONS

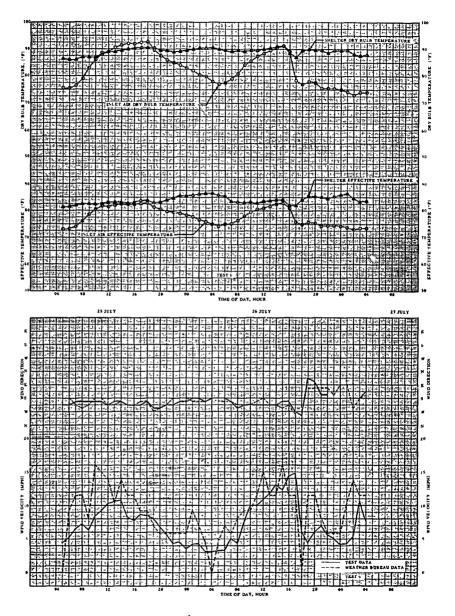
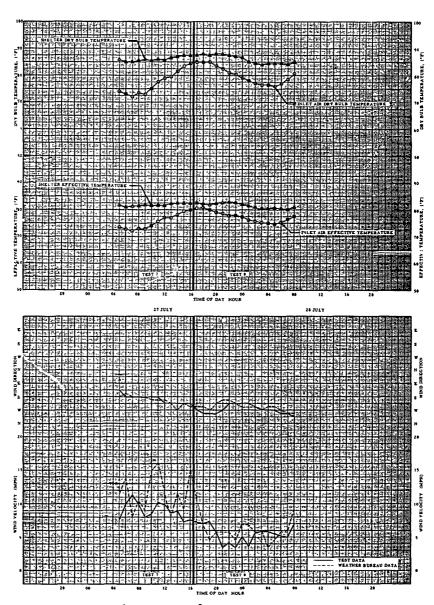


Figure 25 TEST 6 TEMPERATURES AND WIND CONDITIONS



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Figure 26 TESTS 7 AND 8 TEMPERATURES AND WIND CONDITIONS

5.4 Error Analysis

The following analysis is made in order to evaluate the accuracy of the indicated ventilation rate as measured by equation 1.

Given a function of n number of variables, the relative error in P, $\frac{d(P)}{P},$ is defined as

$$\frac{d(b)}{d(b)} = \frac{1}{2} \left[\left(\frac{Qx^1}{Qb} \right) \cdot q(x^1) + \left(\frac{Qx^2}{Qb} \right) \cdot q(x^2) + \dots + \left(\frac{Qx^n}{Qb} \right) \cdot q(x^n) \right]$$
(3)

where:

d(P) = absolute error in the property, P

 $d(X_1)$ = absolute error in the variable, X_1 , due to experimental measurement

 $\frac{\partial P}{\partial X_1}$ = absolute error contribution to the property, P, due to the variable, X_1 , with all other variables held fixed.

Using this method, an estimation of the relative error in the measured air flow is made in this section.

Applying the above discussion to equation 1, the relative error in the measured ventilation rate is:

$$\frac{d(Q)}{Q} = \begin{bmatrix} \frac{d(M_w)}{M_w} \end{bmatrix} + \begin{bmatrix} \frac{d(v_o)}{v_o} \end{bmatrix} - \begin{bmatrix} \frac{d(W_s - W_o)}{(W_s - W_o)} \end{bmatrix}$$

$$(4)$$

The water input to the shelter was measured to the nearest half-pound, thus $d(M_W) \leq \pm 0.25$. The specific volume, v_o , can be read from the psychrometric chart within 0.1 cubic feet per pound of dry air, so $d(v_o) \leq \pm 0.05$. Drybulb and wet-bulb temperatures were read to the nearest half-degree giving a corresponding inaccuracy to the humidity ratio of $d(W_S - W_o) \leq \pm 0.0005$ (from the psychrometric chart).

Therefore.

$$\frac{d(Q)}{Q} = \left[\frac{\pm 0.25}{M_W}\right] + \left[\frac{\pm 0.05}{v_o}\right] - \left[\frac{\pm 0.0005}{W_s - W_o}\right]$$
(5)

Throughout the test these relationships held.

$$M_{\rm w} \ge 12.0$$
 lbs/hr

$$v_0 \ge 13.0 \text{ ft}^3/16$$

Therefore, considering the relative magnitudes of the terms in equation 5, the relative error can be approximated as

$$\frac{d(Q)}{Q} \le \frac{0.0005}{W_0 - W_0}$$

and for periods when

$$[W_s - W_o] \ge 0.0020,$$

we have

$$\frac{d(Q)}{Q} < 0.25$$

or the maximum possible error due to measurement in the measured air flow rate is less than 25 percent. Table 4 summarizes the measurement error for various humidity ratio differences and indicates the corresponding number of hourly data points that are available for analysis.

Table 4 Measurement Error

[Ws-Wo]	Max. Possible Erro.	No. of Data Points
≥ 0.00100	< 50.0%	225
≥ 0.00150	< 33.3%	164
≥ 0.00200	< 25.0%	132

NOTE: As W -W decreases, you are in effect including points which have higher ventilation rates.

5.5 Adequacy of Natural Ventilation

With the aid of results from a companion study (Ref. 9) conducted at GARD it is possible to establish adequacy limits for a shelter located in Chicago and ventilated by natural ventilation only. The results of the study are presented in the form of adequacy curves which were generated based upon ten years of hourly Weather Bureau recordings of wind condition and wet and dry-bulb temperatures. Once the EA value for a particular shelter is known, the adequacy curve can be entered and for a desired maximum shelter effective temperature the adequacy of natural ventilation determined.

For the Chicago shelter, an overall window effectiveness factor of 0.15 was calculated. Assuming that the maximum open window area is obtained when the bottom sash of each window is raised to its extreme, the total area available for inlet air, assuming equal inlets and outlets, is 119 square feet. Using all available floor area that has a radiation protection factor of greater than 40 (see Section 2.4), the maximum occupancy level at 10 square feet per person is 275 occupants. The EA value of the shelter can then be established as:

EA = $\frac{0.15 \times 119}{275}$ = 0.065 square feet per occupant

Entering the abscissa of Fig. 27 at a value of EA = 0.065 square feet per occupant and for a limiting shelter ET of 83°F, the adequacy of natural ventilation for this shelter is 0.982. This means that 98.2% of the time, or for all but seven of the days during the year natural ventilation will adequately ventilate the shelter such that the ET will not rise above 83°F with 275 occupants within the shelter.

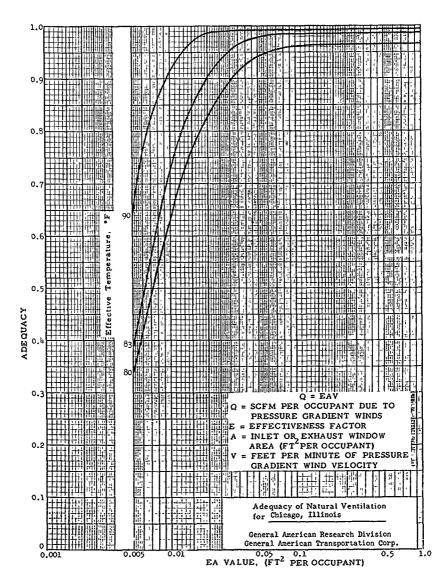


Fig. e 27 NATURAL VENTILATION ADEQUACY CURVE FOR CHICAGO, ILLINOIS

If the occupancy density is lowered to 8 square feet per occupant, 344 occupants will be able to be housed within the shelter and the resultant value of EA is 0.052 square feet per occupant. The adequacy for the same limiting shelter ET of 83°F is then reduced to 98.0%. This change is negligible.

If the lowest E recorded in Table 2 for the 90° wind sector analysis was used instead of the overall E, the resulting change in adequacy is less than one percent. The overall E can therefore be used as a design value for a corridor-type shelter located in Chicago.

5.6 Comparison of Ventilation Rates

A simplified equation for estimating natural ventilation due to wind forces for aboveground structures has been proposed by Dr. Richard Condit of Stanford Research Institute (Ref. 10). His work is based upon building codes for various sections of the country, and upon design values of wind speeds which are set forth in the 1963 ASHRAE Guide and Data Book. The following equation resulted:

cfm/man = (floor area in sq. ft./man) x (wind speed in mph) (6)

For the wind speed Dr. Condit suggests that the adjusted ASHRAE hot weather design values (Ref.11) of H (high) = 5.5 mph, M (medium) = 3.5 mph, and L (low) = 2.0 mph be used. For Chicago the design value wind speed is M or 3.5 mph. Using 10 square feet of floor area per man, Dr. Condit's equation predicts 35 cfm/man which gives a ventilation adequacy of 97.7%.

The expected ventilation rate for this shelter can be calculated using the equation Q = EAV and the experimental values for effectiveness factor (0.15) and average wind speed (7.4 mph) obtained from these tests. If we

assume that one-half of the openable window area of the shelter acts as an air inlet, then F, the unequal inlet-outlet area factor, equals 1.0, and A=119 square feet. It follows that the ventilation rate per shelteree is

$$Q = 88(1.0)(0.15)(119)(7.4)/275 = 42.3 \text{ cfm/man}$$

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Therefore, Condit's formula predicts a ventilation rate about 20% less than the rate derived from the average experimental results. With this particular shelter, Condit's method appears to be useful for predicting general expected ventilation rates.

SECTION 6

CONCLUSIONS AND RECOMMENDATIONS

The following conclusions and recommendations are made based on the test data:

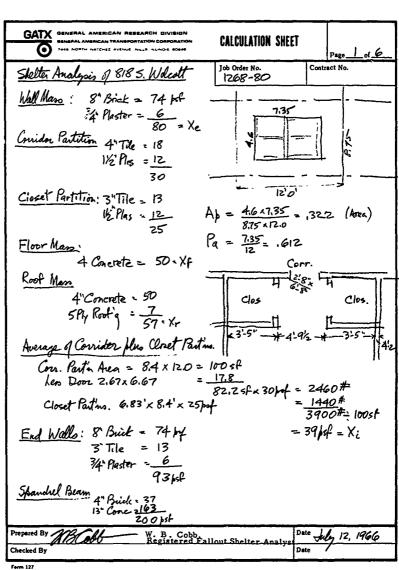
- An overall window effectiveness factor of 0.15 was obtained from the correlation between wind speed and ventilation rate. This window effectiveness factor is independent of wind direction.
- 2. The shelter will be adequately ventilated 98.2% of the days during the year. This estimate is based upon a compilation of ten years of Weather Bureau data and a calculated EA value of 0.065 sq ft/occ for the shelter.
- Half the windows functioned as inlets and half as outlets based upon ASHRAE E-factor analysis.
- 4. In general, the highest winds occurred during the warmest period of the day (1200-1600 hours), and some air movement was observed at all times with the hourly averaged wind velocity never being lower than 2.0 mph.
- 5. Future natural ventilation work should center around three objectives:
 - a. Run modeling studies using a low speed wind tunnel to test scale models of actual buildings already tested and then formulate a law to predict natural ventilation.
 - b. Determine adequacy curves for natural ventilation of building located in other cities than Chicago using existing weather data.

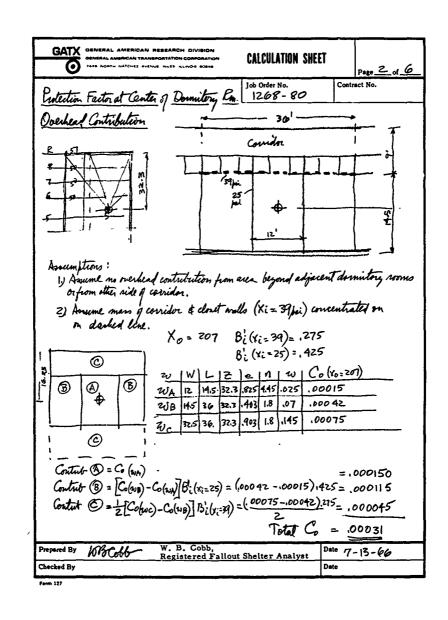
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- Personal Communication with Dr. R. I. Condit of Stanford Research Institute, Menlo Park, California.
- ASHRAE, op. cit., Table I, p. 470.
- 12. ASHRAE, op. cit., Fig. 7, p. 107.

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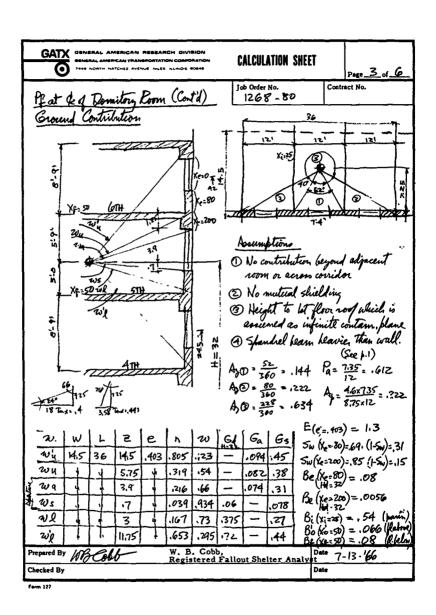
APPENDIX A PROTECTION FACTOR ANALYSIS FOR STUDENT RESIDENCE HALL





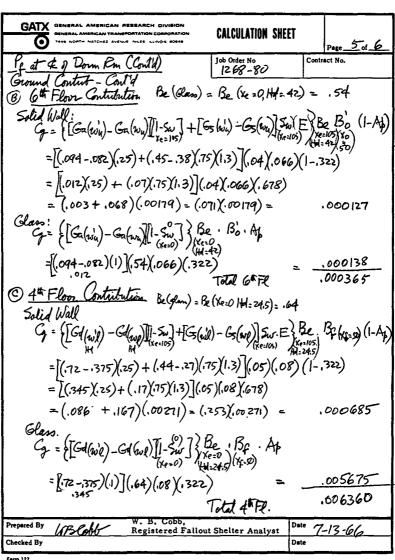
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CALCULATION SHEET Contract No. Story a Detector (5th Flore) Be (fors) = Be (xe=0, Hd=321) = .59 1268-80 Stup of Wall above Windows: (Futition Bldz w/o Partin) (g = {[Ga(ey)...G(ex)]!.Sw) +[Gs(ex)...-Gs(ex)] Sw. E} Be(Ke=2ND) = = [(.082-.074)(.15)+(.38-.31)(.85)(1.3)].0056 (,0012 + ,0772),0056 .000438 Solid Wall except about windows: Cg = { [G(hw, H) - Pa.G(ws, Hd) + (1-Pa)(Ga(ku))][1-Sw(xe-80)] + [(1-Pa) Gs(uk) + Gs(uy) - Pa Gs(us)] Sw(Ke=80) E(e) Be (Ke=80) = { [375-(612x.06)+(388x.074)(3)+[(388x.31)+,27-(.612x.078)],69(13),08 80. [(19.77.4.0 - 75.+ 21.) + (15.870. + 7360. - 375] (.367)(.31)+ (.3423)(91)].08=(.1137+.3113)(08)-(.425)(.08)= .034000 Glaso: Glaso: Galas, H)+Galas) [-Sul(10=0)] Be (Xe=0) (1H=32) = .612 [(.06+.074)(1)]. 59 = (.612)(.134)(.59) =. Total for Floor of Detector (5th) = .0828 For floors above & below, average out weight of wall: (12x1.85x200) + (12x6,9x80) = 1060 = 105/4 Sw(Ke=105)=,75 (1-5w)=.25 Be (xe=105 H= 42)=.04 Be (xe=105 H=245)=.05 (CONFLOW) Date 7-13-66 Registered Fallout Shelter Analyst

Form 127



CALCULATION SHEET Page 6 of 6 Pe at Down. Em & (Could) Contract No. Job Order No. 1268-80 Cornered Contribution - Recap. Detector Floor - 5th = .082800 Floor Abril 6 = .000365 Floor Below - 4 = .006360 Total = .0895/25 Hove assumes complete fictitions bldg of uniform perimeter. Now apply azimuth angle fraction Az 1 Contribution = 10895 x , 144 (63) = A (2) " = .0895 X,222 X 154 = .0107 A (2) ... Total Grand Contrib. = 102360 " Rog Contrib = .00031 Total Re .02391 Protection Factor = Re : 1239, = 42 at center of Domitory Room. In other words, approximately half of the dornitory room (the half away from the windows) qualifies as a fallout shelter. The corridor is obviously bitter, approximately Pr = 110 W. B. Cobb. Date 7-13-66 Registered Fallout Shelter An Checked By

P

23.73 APPENDIX B EQUATIONS FOR THE TABLES OF EFFECTIVE TEMPERATURES AND HUMIDITY RATIOS AS A FUNCTION OF WET AND 3 DRY-BULB TEMPERATURES

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E.

The tables are based on these relationships:

ET =
$$\frac{107.5 \text{ (DB-WB)} + 62.3 \text{ WB}}{62.3 + \text{DB} - \text{WB}}$$

where:

ET. = Effective temperature, °F

DB = Dry-bulb temperature, °F

WB = Wet-bulb temperature, °F

This relationship is limited to low air velocities and is restricted to the temperature range of

45°F < DB < 110°F

30°F < WB ≤ 100°F

Effective temperatures from these tables have an error of less than 0.5°F as compared to those determined from the ASHRAE Effective Temperature Nomogram (Ref. 12).

To determine the humidity ratio, Dalton's rule and perfect gas mixture relations are applied:

$$W = 0.622 \left[\frac{P_W}{P - P_W} \right]$$

where:

W = Humidity ratio, lbs water/lb dry air

P = Partial pressure of water vapor

P = Barometric pressure (sea level assumed) (P_w and P in consistant units)

$$P_{W} = P_{S} - \left[\frac{(P - P_{S})(DB - WB)}{2831 - 1.43 WB} \right]$$

where:

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C KE

$$P_s$$
 = Saturation pressure of water vapor at wet-bulb temperature WB $(P_w, P_s$ and P in consistant units)

Accuracy is 0.5% or better for all but the lowest humidity ratios.

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By R. H. Henninger and C. A. Madson August 1966 (UNCIASSIFIED), pp. 81 Interim Report 1268-81 OCD Work Unit 1214A

type shelter located in Chicago. The effective temperature of this shelter when occupied at a density of 10 square feet per person will not exceed 83°F for more than seven days during an average year. This shelter. The discussion of the results is preliminary and should not The results are reported on a natural ventilation test of a corridorinterim report describes environmental tests performed in a specific be used as the basis for general conclusions. A subsequent final report will include a comparative e aluation of data from subsequent tests having a variety of configurations and locations.

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